AFCRL-TR-74-0574

ADA019303

STUDY OF ELECTRONIC TRANSPORT AND BREAKDOWN IN THIN INSULATING FILMS

Walter C. Johnson
Wilmer R. Bottoms

Princeton University
Department of Electrical Engineering
Princeton, New Jersey 08540

July 1974

Semi-Annual Technical Report No. 4

Sponsored by:

Defense Advanced Research Projects Agency
ARPA Order No. 2180

Monitored by:

AIR FORCE CAMBRIDGE RESEARCH LABORATORIES
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
HANSCOM AFB, MASSACHUSETTS 01731

ARPA Order No. 2180

Program Code No. 4D10

Contractor: Princeton University

Effective date of contract: 1 July 1972

Contract No. F19628-72-C-0298

Principal Investigator and phone no.
Prof. Walter C. Johnson/609 452-4621

AFCRL Project Scientist and phone no.
Dr. John C. Garth/617 861-4051

Contract expiration date: 30 June 1975

Qualified requestors may obtain additional copies from the Defense Documentation Center. All others should apply to the National Technical Information Service.

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

(19) REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER (18) AFCRL-TR-74-0574	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) (6) STUDY OF ELECTRONIC TRANSPORT AND BREAKDOWN IN THIN INSULATING FILMS		5. TYPE OF REPORT & PERIOD COVERED Scientific - Interim
		6. PERFORMING ORG. REPORT NUMBER Semi-Annual Tech. No. 4
7. AUTHOR(s) (10) Walter C. Johnson, Wilmer R. Bottoms		8. CONTRACT OR GRANT NUMBER(s) (15) F19628-72-C-0298, ARPA-Order-2180
9. PERFORMING ORGANIZATION NAME AND ADDRESS Princeton University, Department of Electrical Engineering, Princeton, New Jersey 08540		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Project No. 2180, DoD Element 61101D
11. CONTROLLING OFFICE NAME AND ADDRESS Air Force Cambridge Research Laboratories (LQ), Hanscom AFB, Massachusetts 01731, Contract Monitor: John C. Garth/LQR		12. REPORT DATE (11) July 1974
		13. NUMBER OF PAGES 13
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) [redacted] (12) 14p.		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

A - Approved for public release; distribution unlimited.

ACCESSION for		
NTIS	White Section	
DDC	Buff Section	
UNANNOUNCED		
JUSTIFICATION		
BY		
DISTRIBUTION/AVAILABILITY CODES		
Dist.	AVAIL. and/or SPECIAL	
A		

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

(9) Semi-annual technical rept.,

18. SUPPLEMENTARY NOTES

This research was supported by the Defense Advanced Research Projects Agency. ARPA Order No. 2180

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Dielectric Breakdown
Insulating Films
Corona-Induced Breakdown
Self-Quenched Breakdown
Silicon Dioxide

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

An overview is given of progress in the study of high-field electronic transport and dielectric breakdown in thin (1000-5000 Å) insulating films on silicon. The principal results to date are on SiO_2; also under study are Al_2O_3, Si_3N_4, and layered composites. The studies include corona-induced nondestructive breakdown, self-quenched breakdown, effects of electron irradiation, study of charge-carrier trapping, study of lateral nonuniformities, electron-beam probing of the insulator-semiconductor interface, and theoretical modeling of hot-electron distributions and of localized breakdown.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

Unclassified 400 734

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

PRECEDING PAGE BLANK-NOT FILMED

I. INTRODUCTION

The purpose of this report is to provide an overview of progress in a research program directed toward a basic understanding of electronic transport, charge trapping, and dielectric breakdown in the thin insulating films used in integrated circuits. The films being studied are silicon dioxide, aluminum oxide, silicon nitride, and their layered composites, on silicon substrates. The purpose of the program is to provide a correct and quantitatively accurate understanding of the physical processes leading to breakdown of the films, with the ultimate objective of providing a rational basis for the choice of materials, processing methods and treatment of insulating films for increased yield in manufacturing and greater reliability in use. The results obtained in each of the various aspects of this program are being presented in a comprehensive and detailed manner in a series of Special Reports, some of which have already been issued and others of which are in various stages of preparation.

Separate sections in this report are devoted to corona-induced nondestructive breakdown, studies of breakdown by the self-quenched technique, charge-discharge studies of charge-carrier trapping in insulating films, investigation of the effects of low-energy electron irradiation of insulating films, electron beam studies of semiconductor-insulator interfaces, a study of lateral nonuniformities in metal-insulator-semiconductor structures, and theoretical modeling of hot-electron distributions and of localized breakdown.

II. CORONA-INDUCED NONDESTRUCTIVE BREAKDOWN OF INSULATING FILMS

(Z.A. Weinberg, H.S. Lee and H.H. Chao collaborating)

The use of a corona discharge in a gas at atmospheric pressure to contact the unmetallized surface of an insulating film provides a convenient means of inducing charge transport across the insulating film, and the virtual absence of lateral surface conduction allows the use of very high field intensities - tantamount to breakdown - without destruction of the films. We have developed the corona-charging technique together with auxiliary new techniques such as the use of the charge-separating property of a PN junction to identify the principal charge carrier in the insulator and the use of a

comparison method for measuring the steady-state surface potential of the insulator during charging, and have applied these to a study of charge injection, transport, and trapping in SiO_2 films on Si. In support of the experimental work, a theoretical study has been made of the tunneling of electrons into the insulator from the thin potential well formed in the semiconductor by strong band bending under high-field conditions. The PN junction technique has been described in a Special Report on this contract[1] and in a published paper.[2] A manuscript on the comparison method for measuring insulator surface potential is being issued as Special Report No. 5 on this contract, and has been accepted for journal publication.[3] A paper on the corona technique and results obtained by this method on SiO_2 has been submitted for journal publication and will soon be submitted to AFCRL for permission to publish and distribute as a Special Report on this contract.[4] Also prepared for journal publication and soon to be submitted as another Special Report is a paper on the theory of the tunneling of electrons from a semiconducting substrate into an insulator.[5]

Because the corona technique has proved to be remarkably convenient and productive in the study of high-field effects in thin insulating films, we are enlarging the scope of this study. Mr. H. S. Lee is studying transport and trapping in SiO_2 films at current densities that are considerably greater than those investigated previously, using both positive and negative polarities of corona, and he is also studying the use of gases other than dry air. Deep electron traps, not previously present in the oxide, are observed after exposure of the SiO_2 to sufficiently intense positive corona. The generation of deep electron traps under high-field conditions has important implications in regard to the spatial concentration of electric field under breakdown conditions.

Mr. H. H. Chao is preparing equipment for the simultaneous use of corona charging with UV and vacuum UV excitation. The use of corona ions to provide the electric field in the insulator eliminates the need for a metallic field plate and should remove the ambiguity arising from the photoelectric emission of carriers from a metallic electrode. A similar experiment with this degree of sophistication has not, to our knowledge, been set up

in the past. Sub-bandgap UV excitation will be used to produce internal photoemission of carriers from the substrate, and vacuum UV excitation will be used to produce hole-electron pairs in the insulator itself.

III. SELF-QUENCHED BREAKDOWN OF INSULATING FILMS (D.Y. Yang collaborating)

In these studies we use metal-oxide-semiconductor structures in which the metallization is very thin (200-1000 Å). When a voltage is applied to the structure and a localized breakdown occurs in the insulating film, the Joule heat evolved in the immediate vicinity of the breakdown results in the removal of the thin metal about this point; thus the breakdown, although locally destructive, is self-quenching. The time evolution of the breakdown, the charge storage after breakdown, the effect of substrate type (p or n) and of polarity, and the physical features as observed by optical microscope and scanning electron microscope, all furnish information regarding the mechanisms and parameters relevant to the breakdown.

Most of our experiments have been performed on films of SiO_2 thermally grown on (100) Si substrates to a thickness of approximately 2500 Å. Both p and n substrates were used. The metallization was of aluminum, about 1000 Å in thickness. Upon the occurrence of a breakdown event, the rate of discharge of the capacitor energy corresponded to a series resistance of about 100 ohms when the substrate was in accumulation, and to several thousands of ohms when the substrate was in inversion, indicating that the discharge was controlled by the spreading resistance offered by the substrate. Each of the four possible combinations (p or n substrate, + or - field-plate polarity) showed its own distinctive properties and its own distinctive configuration of breakdown damage. Some properties correlated with the nature of the substrate surface channel (inversion versus accumulation); other properties correlated with the field-plate polarity. With a p-substrate and positive field-plate polarity, the region of removal of metal tended to be square, with the sides of the square parallel to the (100) axes of the substrate. This effect is attributed to the anisotropy of hot-electron conduction in the (100) plane of the substrate, a conclusion which has been confirmed by further studies using other samples with different

oxide thicknesses and therefore having different breakdown voltages. As the breakdown voltage was made greater, the breakdown pattern evolved from round to square and finally to the form of a four-pointed star with the points along the [110] directions.

In order to study the initiation mechanisms of the breakdown, electrical measurements were made in the pre-breakdown region. The results of steady-state I-V and C-V measurements were consistent with the conclusion that the pre-breakdown currents in the SiO_2 were caused by Fowler-Nordheim tunneling. Electric field intensities in excess of about 7.6×10^6 V/cm resulted in current instabilities which were found to be closely related to the appearance of positive charges in the SiO_2. An instability in the current could be induced by cooling the sample at a constant bias voltage. This can be interpreted as due to the larger mean free path of electrons at the reduced temperature, resulting in a greater production of hole-electron pairs through impact ionization. Trapping of the holes near the electron-tunneling contact enhances the electric field at this contact and increases the tunneling current. We believe that these experiments provide the first direct evidence of the role of impact ionization in the runaway process at the onset of breakdown.

A paper describing some of the results of these studies has been published[6] and has also been issued as Special Report No. 3 on this contract.[7] A second paper[8] is almost ready for submission. A comprehensive report on the results of these studies will be issued as Special Report No. 4 on this contract.[9]

IV. CHARGE-DISCHARGE STUDIES OF CHARGE-CARRIER TRAPPING IN INSULATING FILMS*

(N. M. Johnson and J. Clement collaborating)

We have designed and constructed apparatus for the convenient exploitation of charge-discharge techniques for the probing of deep traps in thin insulating films, and we have used this equipment and these techniques in a study of the electron traps produced in silicon dioxide by the implantation of aluminum and neon ions. The equipment includes a high-vacuum sample chamber, a sample holder arranged for convenient manipulation from the outside and

*This work was also supported in part by DNA under sponsorship of NRL (ONR Contract N00014-67-0151-0035).

provided with means for heating and for cooling to liquid nitrogen temperature, a soft X-ray generator for excitation of the insulator to produce hole-electron pairs, a high-intensity monochromator arranged for internal photo-emission of carriers into the insulating film and for photon excitation of trapped carriers, and appropriate electronic instrumentation including provision for the exploitation of the MIS measurement techniques for determination of charge storage and density of interface states. This equipment makes a wide variety of trap-probing techniques conveniently available, and is used as an important adjunct in other experimental studies.

Our study of electron traps in ion-implanted SiO_2 films was motivated by the observation that ion implantation can improve the radiation hardness of MOS structures under positive gate bias and from the speculation that the improvement is caused by increased electron trapping which balances the effect of the strong hole trapping that is always present in the metal-SiO_2-Si structure. Our studies showed that thermally grown SiO_2 that has been implanted with aluminum ions possess much larger concentrations of electron traps than are found in normal SiO_2. The traps are deep, requiring photon energies in excess of 4.0 eV for photodepopulation of trapped electrons. A thermal anneal at 600°C for 30 minutes substantially reduced the number of electron traps, leading to the conclusion that a large proportion of the traps were associated with displacement damage created by the ion implantation. A further indication of the correctness of this conclusion was obtained from preliminary measurements taken on neon-implanted samples, in which deep electron trapping was found to be approximately the same as in aluminum-implanted samples, indicating that the displacement damage, rather than the electronic activity of the implanted ion was the major factor.

A Special Report[10] has been issued on the foregoing work and a shortened version has been accepted for publication.[11] In addition to the work already reported, we have made a more careful study of the effect of neon implantation as compared with implantation with aluminum and have verified the similarity in electron trapping between the two. We have also found an important fluence-related effect in implanted SiO_2, i.e., there

appears to be an optimum concentration of trapping centers; too large a concentration leads to instability of the trapped charge. The instability is not sensitive to temperature and may be associated with charge-carrier hopping between adjacent centers. Further studies planned for the immediate future include: (a) Hole-trapping properties of the implantation-produced centers and the effectiveness of the centers in promoting hole-electron recombination. Although we have established the presence of large concentrations of electron traps in the implantation-hardened SiO_2 films, the actual mechanism of hardening — whether by enhanced recombination or charge balancing by electron trapping — has not been established. (b) The effect of ion implantation on the dielectric breakdown properties of the insulating films. (c) A systematic study of the effects of heat treatment. This important subject has not yet received sufficient attention, both from a practical, phenomenological point of view and also from the basic aspect of the electronic activity of the implanted impurity atoms themselves.

V. LOW-ENERGY ELECTRON IRRADIATION OF INSULATING FILMS* (C.T. Shih collaborating)

If a quasi-ohmic contact can be made to an insulator, the structure of the resulting I-V characteristic can serve as a powerful probe of traps in the insulator. We have used a low-energy (1-5 kV) electron beam to inject electrons through a thin metallization and shallowly under the surface of an insulator in order to provide a reservoir of free electrons which would serve as the desired contact. The silicon substrate, biased positively, serves as the anode. The electron beam, in addition to supplying electrons to the reservoir, creates hole-electron pairs throughout its range in the insulator and also generates photons with a wide spectrum of energies. The current-voltage characteristics that we have observed in thermally grown SiO_2 under these conditions suggests a trap-dominated space-charge-limited current ($J \propto V^2$) with detrapping of the electrons stimulated by beam-generated photons. The concentration of traps required in this interpretation is much greater than that observed in unirradiated thermally grown oxides, and furthermore the traps must be in the bulk rather than entirely at the interface. For this explanation to be correct, the electron irradiation must have been

*This work was also supported in part by DNA under sponsorship of NRL (ONR Contract N00014-67-0151-0035).

responsible for the generation of electron traps beyond the range of the beam itself.

In order to obtain independent evidence regarding the foregoing interpretation, we conducted a charge-discharge study of electron trapping both before and after electron-beam irradiation, using the apparatus described in Section IV. The results confirmed the generation in SiO_2 of deep electron traps by irradiation with a nonpenetrating electron beam.

Inasmuch as relatively little had been reported in the literature regarding the effects of low-energy electron irradiation on SiO_2, and the results reported indicated positive, not negative, charge trapping, we conducted a study of the effect of beam energy in the range up to 15 kV. The results of this study show that electron trapping dominates at the lower energies but that positive charge trapping dominates at higher energies regardless of fluence.

An extensive Special Report on the results of these studies is in preparation.[12]

VI. ELECTRON BEAM PROBE STUDIES OF SEMICONDUCTOR-INSULATOR INTERFACES

(D. Guterman and P. Rotiman collaborating)

An electron beam of diameter as small as 100 Å may be employed to study MOS structures providing information about the surface topography (secondary electron imaging), surface chemical composition (Auger electron spectroscopy), bulk chemical composition (X-ray fluorescence), as well as the structure of interface regions at high spatial resolutions. The penetration depth of the beam and therefore the excited volume can be altered by adjusting the accelerating voltage and the incident angle. Images of the internal surfaces of MOS structures are formed due to variations in the metal-insulator barrier height, the semiconductor-insulator barrier heights, defects within the oxide or at the interfaces, and topography causing localized high-field conditions. These mechanisms give rise to small ac signals in the current induced across the structure by the electron beam. The signals may be amplified and used to modulate the intensity on a CRT. Several different structures have been observed at the interfaces in MOS

systems using this technique. Electrical measurements and bias thermal stressing experiments have been used to determine the nature of the structures responsible for observed images.

A paper describing these studies has been accepted for publication and will be issued as a Special Report on this contract.[13]

VII. STUDY OF LATERAL NONUNIFORMITIES IN MIS STRUCTURES* (C.C. Chang collaborating)

The flatband voltage of an MIS structure, as obtained by a C-V measurement, provides a convenient measure of the charge stored in the insulating layer. (A mercury probe can be used for temporary metallization of the insulator surface if the sample is normally unmetallized, as is true in corona studies.) However, many of our experimental procedures, such as bias-temperature stressing, exposure to corona, application of large electric fields, and irradiation by electrons, produce a stretch-out of the C-V curve. This can be caused by either of two quite different phenomena: fast interface states or laterally nonuniform charge storage. It is important to the interpretation of the experimental results to identify correctly the cause of the C-V stretch-out and to characterize the results accurately.

The separation of the effects of lateral nonuniformities from those of fast interface states is not a trivial matter. Several proposals have been made in the literature, including the use of the voltage dependence of the high-frequency conductance or the calculation of an effective doping profile of the semiconducting substrate which is compared before and after C-V stretch-out. We are evaluating various proposals both theoretically and experimentally and are studying additional methods such the frequency dependence of the C-V curves. For the characterization of lateral nonuniformities, we have written a computer program which extracts the distribution of flatband voltages from the high- and low-frequency C-V curves.

VIII. THEORETICAL MODELING (Professors M.A. Lampert and Brian Ridley collaborating)

Monte Carlo calculations have been made of hot-electron distributions produced by high electric fields in insulating films. The results show that when the mean free path increases with increasing energy, some electrons escape from the well behaved part of the distribution and gain large energies.

---

*This work was supported in part by Bell Telephone Laboratories, Inc.

A Special Report is planned on this subject.

A model of insulator breakdown has been explored. This is based on Fowler-Nordheim injection from a cathodic protuberance, filamentary joule heating, and activation of positive ions which enhance the injecting field. A mechanism for lateral spreading of the initial discharge and subsequent quenching by the substrate resistance gives the extent of the damaged area to be of the observed order in self-healing breakdowns. The breakdown field and its dependence on film thickness is in reasonable agreement with experiment. A Special Report on this work has been prepared and will soon be submitted.[14]

PRECEDING PAGE BLANK-NOT FILMED

References

1. Z. A. Weinberg, Walter C. Johnson and Murray A. Lampert, "Determination of the Sign of Carrier Transported Across SiO_2 Films on Si," Special Report No. 2 on this contract, AFCRL-TR-74-0206, April 1974.

2. Z.A. Weinberg, W. C. Johnson and M. A. Lampert, Appl. Phys. Lett. 25, 42 (1974).

3. Z. A. Weinberg, D. L. Matthies, W. C. Johnson and M. A. Lampert, "Measurement of the Steady-State Potential Difference Across a Thin Insulating Film in a Corona Discharge."

   (a) Special Report No. 5 on this contract, AFCRL-TR-74-0315, October 1974.
   (b) Rev. Sci. Instrum. 46 (Feb. 1975).

4. Z. A. Weinberg, W. C. Johnson and M. A. Lampert, "High-Field Transport in SiO_2 on Si Induced by Corona Charging of the Unmetallized Surface," submitted to J. Appl. Phys., will be ussued as a Special Report on this contract.

5. Z. A. Weinberg, W. C. Johnson and M. A. Lampert, "Theory of Tunneling Out of a Triangular Potential Well Through a Triangular Barrier, With Application to the Si-SiO_2 Interface," will be issued as a Special Report on this contract.

6. D. Y. Yang, W. C. Johnson and M. A. Lampert, Appl. Phys. Lett. 25, 140 (1974).

7. D. Y. Yang, W. C. Johnson and M. A. Lampert, "Scanning Electron Micrographs of Self-Quenched Breakdown in Al-SiO_2-(100)Si Structures," Special Report No. 3 on this contract, AFCRL-TR-74-0278, June 1974.

8. D. Y. Yang, W. C. Johnson and M. A. Lampert, "The Anisotropy of Self-Quenched Breakdowns in Al-SiO_2-(100) p Si Structures," to be published.

9. D. Y. Yang, Walter C. Johnson and Murray A. Lampert, "A Study of the Dielectric Breakdown of SiO_2 Films on Si by the Self-Quenching Technique," Special Report No. 4 on this contract, AFCRL-TR-74-0516, October 1974.

10. Noble M. Johnson, Walter C. Johnson and Murray A. Lampert, "Electron Trapping in Ion-Implanted Silicon Dioxide Films on Silicon," Special Report No. 1 on this contract, AFCRL-TR-74-0133.

11. N.M. Johnson, W. C. Johnson and M. A. Lampert, "Electron Trapping in Al-Implanted SiO_2 Films on Si," J. Appl. Phys., scheduled for publication in March 1975 issue.

12. C. T. Shih, W. C. Johnson and M. A. Lampert, "A Study of the Effects of Low Energy Electron Irradiation on MOS Capacitors," Special Report on this contract, in preparation.

13. W. R. Bottoms and D. Guterman, "Electron Beam Probe Studies of Semiconductor-Insulator Interfaces," scheduled for publication in J. Vac. Sci. Tech., Nov./Dec. 1974.

14. Brian K. Ridley, "Mechanics of Electrical Breakdown in SiO_2 Films," Special Report on this contract, to be submitted soon.